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[Holographic Optical Elements for Liquid Crystal Projectors]

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1. Introduction

A holographic optical element (HOE) is drawing attraction as a flat element capable of performing a given wavefront conversion. Our company has already reported the development of a relief-type HOE. Here, the author will report an example in which a volume-type HOE was applied to liquid crystal display.

The practical application examples of liquid crystal display include a liquid crystal projector and a rear projection TV. Compared with CRT type, the liquid crystal type has the merit that it is lighter and thinner. However, it has a shortcoming that the utilization efficiency of light is less than 10 percent due to the absorption of light by deflection plate and color filter, causing a problem that its display image in a bright room is unable to see clearly.

We have developed a transmissive-type holographic color filter (HCF) having both color separation and focusing capabilities, aiming at improving the light use efficiency of liquid crystal display.[1] Besides this, among the reported methods to increase the light use efficiency there are a method in which three liquid crystal panels are used instead of an absorption type color filter and a method in which three dichroic mirrors and a microlens array are used.[2]

Here, the author describes the principle of HCF's color separation and focusing capabilities and the increase of light use efficiency achieved by setting up a diffraction peak both in the blue and red regions of visible light (hereinafter referred to as two-peak hologram).

2. Principle

We have reported that it was possible to increase the light use efficiency by using a single peak HCF having color separation and focusing capabilities for a liquid crystal projector.[1] Fig. 1 shows the optical configuration of a liquid crystal projector that is composed of a lamp, a HCF, a LCD, a panel, a projection lens and a screen. Fig. 2 shows a schematic diagram to explain the color separation and focusing of HCF. We designed a hologram that corresponded to a pair of RGB of liquid crystal panel pixels and made an arrayed HCF by combining it with the array of panel. If white illumination light with high parallelism

enters this HCF at a designed angle, the individual wavelength of the white light is diffracted at a different angle, separated into the rainbow colors. In addition, by designing that the pitch of interference pattern will change toward the dispersion direction and it will curve toward the vertical direction, it becomes possible to focus the light on the surface of liquid crystal panel. Considering the spectrum of illumination light, parallelism, pixel shape of liquid crystal panel and the thickness of substrate glass facing the liquid crystal, HCF was designed and prepared. Though it changes depending on the pixel shape and other conditions, the light use efficiency increased by 2 to 3 times, compared with a liquid crystal display using an absorption type color filter. However, as a diffraction peak existed in the green region, the white color of projection image was greenish, unlike the case where an absorption type color filter was used. Since the light of a commonly used metal halide lamp contains an emission line whose color is close to green, it is necessary to adjust the white balance by reducing the intensity of green light of a projection image. That is, the adjustment needs to be made as to the region where the degree of improvement is low among the blue, green and red regions. To solve this problem, we have studied a two-peak hologram in which the diffraction efficiency in the green region decreased but that in the blue and red regions increased.

3. Preparation procedure of HCF

Experiments were carried out according to the following procedure.

1. Optical design - Design of interference pattern by ray trace program
2. Making the computer generated hologram (CGH)
3. Duplication to hologram recording material

We have developed a ray trace program that could predict the chromaticity and brightness of a projection image by inputting the spectrum of illumination system, angle distribution, pixel shape of liquid crystal panel and focal distance. Using this program and through the calculations while changing the parameters, an appropriate interference pattern was designed. Then, a relief type CGH having a required interference pattern was prepared through the photolithographic process, which was used as the original plate. The information of the original plate was copied to the hologram recording material by a laser exposure process in order to make the final product or HCF.

4. Two-peak hologram

If the diffraction wavelength of hologram has a single peak and exists in the green region, the white color of projection image becomes greenish. To overcome this problem, a two-peak

hologram that had a diffraction peak both in the blue and red regions was examined. To analyze the behavior of a two-peak hologram, a ray trace experiment was conducted using a volume type diffraction grating as a model. The following are the results when a volume type diffraction grating was used.

To provide two diffraction peaks, two types of independent interference patterns are required. As the methods to realize these, the overlapping use of two diffraction gratings and the double recording on one recording material can be considered. We have studied the former or the overlapping use of two diffraction gratings.

The behavior of two-peak hologram, when two diffraction gratings are overlapped and the illumination light is a complete parallelism light, can be analyzed as shown below. That is, when the diffraction efficiency of two diffraction gratings is assumed to be η_1 and η_2, respectively, the overall diffraction efficiency η is given by the formula shown below. Fig. 3 shows an explanation diagram.

$$\eta = \eta_2(1 - \eta_1) + \eta_1(1 - \eta_2) = \eta_1 + \eta_2 - 2\eta_1\eta_2$$

From this formula, it can be understood that when the two diffraction efficiency values η_1 and η_2 are equal, the diffraction efficiency η when two diffraction gratings are used together becomes 0.5 at a maximum. Fig. 4 shows the calculation

results of diffraction efficiency for the entire visible light region. Here, η_1 and η_2 were calculated using Kogelnik's formula and the diffraction efficiency η for the two peaks was calculated using the above-mentioned formula. For comparison, the case where the peak was single in the green region was also included. In case the diffraction efficiency between two diffraction gratings is close, the diffraction efficiency when two diffraction gratings are used together lowers. Therefore, it is important to provide a difference as large as possible of diffraction wavelength region between one diffraction grating and the other one. A wavelength where the diffraction efficiency of two diffraction gratings becomes equal to each other is better to be set in the green region that is reduced to take the white balance. As shown in Fig. 4, the diffraction efficiency of the two-peak hologram was found to considerably increase in the blue region of 400 - 500 nm and in the red region of 600 - 700 nm.

In the meantime, when the light from the light source is not a perfect parallel light, this formula does not hold. With the increasing parallelism defined by the angle distribution from the main light source, the diffraction efficiency of the green region increases and the diffraction efficiency both in the blue and red regions tends to decrease. This is considered to occur because the peak wavelength changes with the change in the angle of entering light. Fig. 5 shows the results when the

ray was traced while changing the parallelism. In this way, because the diffraction efficiency of hologram changes depending on the angle characteristics of illumination light, a ray tracing in which the angle and wavelength distributions of the illumination light are considered is effective. Considering the ray that was diffracted by each of two holograms, a ray trace program capable of predicting the final luminance and chromaticity was prepared. With this, it became possible to design a hologram in which the angle and wavelength characteristics were taken into account.

Fig. 6 shows the results when the spectroscope measured the wavelength distribution of diffraction efficiency for the two-peak hologram prepared this time. As is apparent in the figure, a characteristic having a shape similar to that in the ray trace results conducted at a parallelism of 0 degree was obtained. From the fact that the bottom of diffraction efficiency in the green region was about 50 percent by actual measurement, the effectiveness of the above-mentioned formula and optical design have been confirmed. Compared with the case of the single peak hologram, the light use efficiency of the two-peak hologram was found to be about 1.5 times higher in the blue region and about 1.3 times higher in the red region. As to the evaluation of projection images, we will examine it in the future.

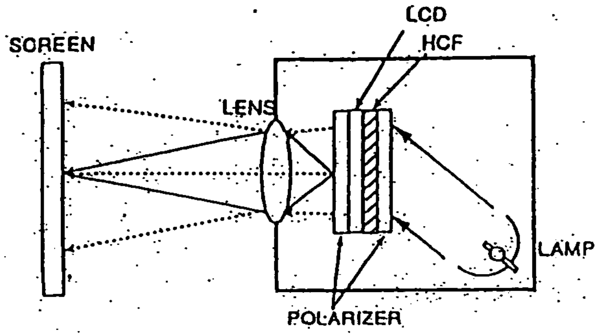

Fig. 1 Optical configuration of liquid crystal projector

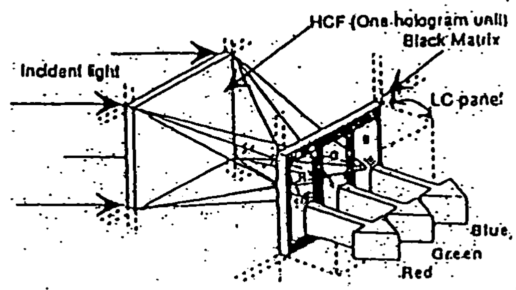

Fig. 2 Schematic diagram to explain the color separation and focusing

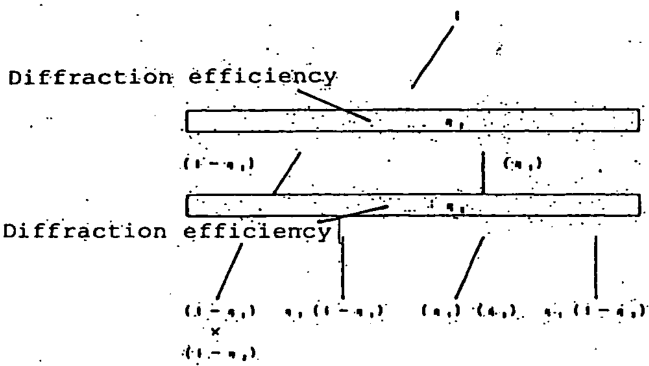

Fig. 3 Diffraction efficiency of two-peak hologram

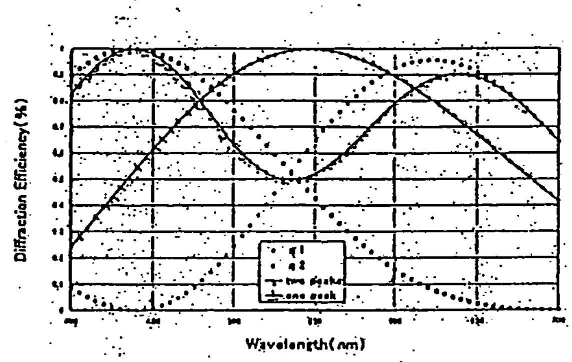

Fig. 4 Calculated values of diffraction efficienc

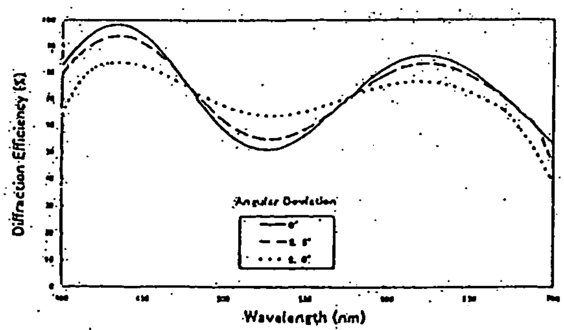

Fig. 5 Parallelism dependency of illumination light

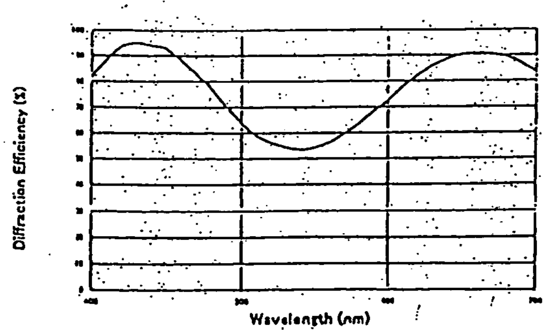

Fig. 6 Measured values of diffraction efficiency